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SHORT-WAVELENGTH LIGHT-EMITTING DEVICES WITH ENHANCED HOLE INJECTION CURRENTS

Final Technical Report
by
Prof. V. A. Kochelap

(May 2005)

United States Army

EUROPEAN RESEARCH OFFICE OF THE U.S. ARMY

London, England

CONTRACT N62558-02-M-6381

National Academy of Sciences
Institute of Semiconductor Physics
Kiev, Ukraine

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Short-Wavelength Light-Emitting Devices With Enhanced Hole Injection Currents**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Academy of Sciences Institute of Semiconductor Physics 45 Prospect. Nauki Kiev 03650 UKRAINE**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**24**	

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2005	Final Report, May 2005

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5. FUNDING NUMBERS

C- N62558-02-M-6381

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EUROPEAN RESEARCH OFFICE
OF THE U.S. ARMY,
Edison House, 223 old Marylebone Road
London, England

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	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	UL	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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In this report we present the results on innovative studies of improvement of the injection currents in group-III nitride-based UV-light-emitting devices. We elaborate two solutions to the problem of low efficiency of p-doping and low injection currents in wide-gap semiconductors. First, the hot-hole injector with appreciably enhanced injection current is proposed and developed to be integrated with commonly used vertical structures of the emitting devices. Second, we develop the alternative design of UV-light sources on the base of lateral $p^+ - i - n^+$ superlattice structures. This design provides for high concentrations of non-equilibrium 2D electrons and holes at modest electric currents and, particularly, aims to improve the hole currents. The lateral design facilitates increasing short-wavelength light emission and its efficiency, as well as extension of the emission of electric current pumped devices to deep UV-range. We also studied the high-field transport and hot electron effects for pumping rare-earth doped nitride electroluminescent devices.
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Keywords: Hole-injection improvement, short-wavelength light-emitting devices, p-doped superlattices, nitride structures, high-field transport, electroluminescence.

Participants of the project: Prof. V. A. Kochelap (PI), Dr. V. N. Sokolov, Dr. A. A. Demidenko, Dr. V. V. Naumov, Dr. T. L. Lynnik, and Dr. L. E. Lokot'.

Table of Contents:

Background:

Recent progress in group-III nitride heterostructure technology open wide perspectives for short-wavelength optoelectronic devices, i. e. light-emitting diodes (LEDs), laser diodes (LDs) and photodetectors, operating from green to deep-ultraviolet spectral range[1,2,3].Development of light emitting devices in this spectral range is stimulated by a number of practically important tasks including high-efficient lightning, high-density optical storage, stimulation of chemical processes, bio-medical applications, etc. Among the latter, the great interest is to UV-biological agent detection [4].
Pumped by the electric current blue LDs and green-, blue-LEDs have been realized on ternary and quaternary structures and are commercially available [5]. Also important results have been obtained in UV photodetecting by using III-nitrides [6]. These two major components of the short-wavelength optoelectronics - UV-emitters and photodetectors - are still in their infancy and need to be studied and developed to reach optimized device performance. Further improvement of performance of group-III-nitride based optoelectronics requires solution of an important problem - obtaining high-density hole currents in bipolar structures. The latter is a complex problem, since it is established that the difficulties in achieving high hole concentrations come from fundamental reasons, most important of them is the deep energy levels of known acceptors [1,2]. Fabrication of heavily p-doped device regions is even more difficult to achieve for AlGaN materials, where energies of the accepter levels are found to be larger [7,8]. Indeed, Mg activation energy in AlGaN increases almost linearly with Al content. At an AlN fraction of 45%, the activation energy *EA* was estimated to be about 0.4 eV. This deepening of the Mg activation energy with Al content presents a real challenge for obtaining *p*-type AlGaN with high Al content
The *low acceptor activation problem* can be overcome in a p-doped superlattice [8], where the average hole concentration can be considerably enhanced because acceptors from barrier layers may supply the holes into quantum wells. Calculations [8] and recent measurements [9] already proved the idea of improved acceptor efficiency in Mg-doped nitride superlattices: the average free hole concentration can be appreciably increased. However the most of the holes ionized from the acceptors are confined inside quantum wells (with the concentrations above 10^{13} cm^{-2} (see Ref. [9]). These quantum wells have potential barriers as high as 100 to 400 meV. These potential barriers depend on both Al-fraction and layer thicknesses, because of the built-up polarization fields. The barriers hinder participation of the holes in the vertical transport required in standard light-emitting devices. Thus, the approach proposed in [8] cannot straightforwardly solve the problem of hole current improvement.

Development of devices with efficient electric regimes of hole injection currents is practically important problem.

Technical results:

The project aims the development of several novel approaches to enhance performance of short-wavelength light emitting devices based on group-III nitride heterostructures. We have identified and developed innovative efficient electrical methods for pumping short-wavelength LEDs and LDs. The first approach employs the vertical electron and hole injection transport typically exploited in LEDs and LDs, and relies on the specially designed hot-hole injectors. The second approach employs the lateral transport and relays on double injection of electron and hole, both confined into quantum wells.
In the project we also studied the high-field transport and hot electron effects for pumping rare-earth doped nitride electroluminescent devices.

Enhancement of hot-hole injection for nitride-based light emitters with vertical electron-hole transport.

To increase the injected hole concentrations and the injection hole current we propose two terminal hole injector schematically presented in Fig. 1 (a). The injector consists of a p-doped superlattice base and two contacts S and D. The injector is separated from the rest of the optoelectronic device by an i-region. A voltage bias applied between the S and D contacts provides lateral hole acceleration and increases the hole temperature T_h, resulting in an enhancement of overbarrier hot-hole concentration. This is known as the real-space transfer effect [10]. Now a light-emitting device can be thought as a three terminal device schematically presented in Fig. 1 (b). A SL hot-hole injector is placed at the top of the structures. A barrier intrinsic layer separates the injector from an n-type doped region, which is supplied by a contact C. The device operates as a charge injection transistor [11]. Let the D-contact be grounded and a positive voltage VS is applied to the S-contact providing lateral hole current and heating of the holes, which results in an enhancement of overbarrier hot-hole injection. Assume that a negative bias V_C is applied to the cathode C. Then both the hot holes from the SL and the electrons from the n-region will be supplied into the *i*-layer, as illustrated in Fig. 1(b). Emission of light occurs in the active i-layer as the result of electron-hole recombination.

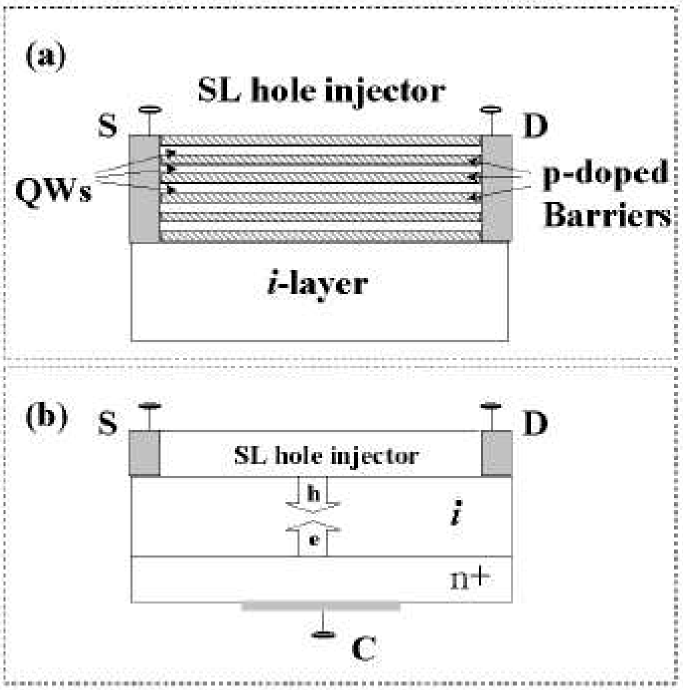


Fig. 1. (a): Schematics of a superlattice hot-hole injector; (b): A light emitting device with enhanced hole injection through hole heating by the electric field.

Since the holes in the nitrides have a large effective mass [1], several subbands are populated in the QWs composing the SL. Then, the estimate for the concentration of the holes moving freely overbarrier is:

$$n_h = n_s \, exp(- U_b/k_B T_h)/L_{QW}.$$

Here, U_b is the barrier height, k_B is the Boltzmann constant, L_{QW} is the thickness of the QWs, n_s is the two-dimensional hole concentration in the QWs related to the average hole concentration in the SL, n_{av}, by the relation

$$n_s = n_{av} \, (L_B + L_{QW}),$$

where L_B is the thickness of the barriers.

A large hole concentration allow one to assume that *h-h* scattering dominates over other relaxation mechanisms and nonequilibrium carrier distributions occur in the form close to the shifted Fermi-Dirac function with an effective hole temperature T_h and a drift velocity V_h, which are the solutions to the momentum- and energy-balance equations

$$d\Pi/dt = e\,E - Q_{\Pi}(T_h, V_h)\ ;$$

$$d\varepsilon/dt = e\,E\,V_h - Q_{\varepsilon}(T_h, V_h).$$

Here Π and ε are average momentum and energy of the holes, E is the electric field, $Q_{\Pi}(T_h, V_h)$ and $Q_{\varepsilon}(T_h, V_h)$ are the rates of momentum and energy relaxation. Momentum relaxation mechanisms include scattering by impurities and by optical phonons. The main energy relaxation mechanism is assumed to be scattering by the optical phonons. Indeed, in the nitrides both the electrons and the holes are strongly coupled to the optical phonons [1]. Specific expressions for Q_p and Q_ε can be found elsewhere.

If the hole concentration and the temperature are known, one can calculate the injection (overbarrier) current, which can be evaluated as a thermoionic current [12]:

$$J = e\,n_s\,(k_B T_h / 2\pi m^*)^{1/2} / L_{QW} \exp(-U_b / k_B T_h),$$

where U_b is the energy height of the barrier.

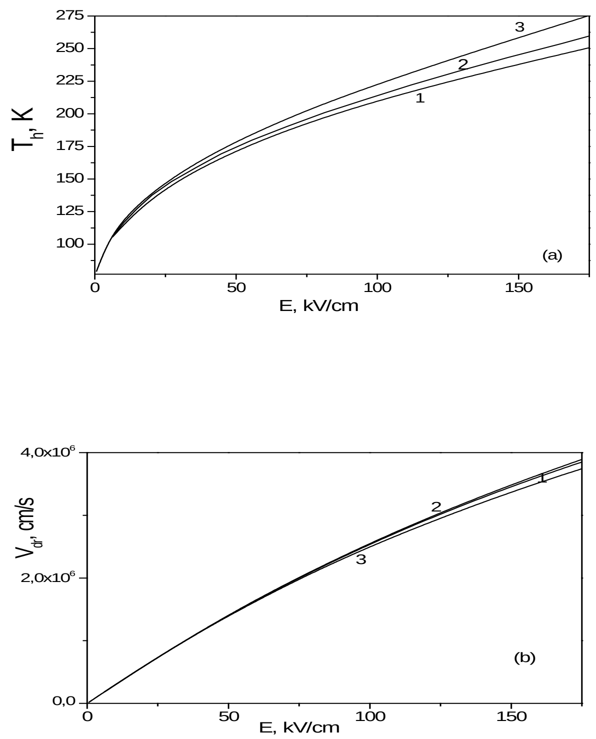
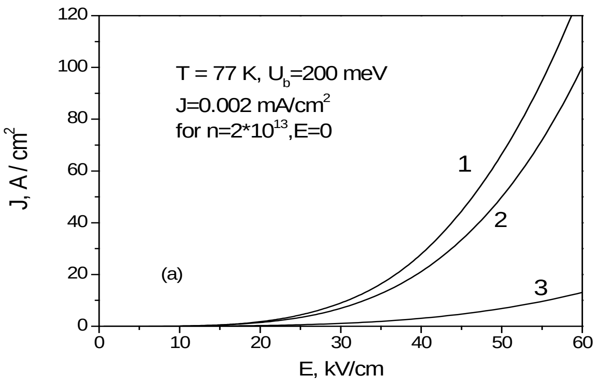


Fig. 2. Hole temperature (a) and drift velocity (b) versus electric field at 77 K and μ=30 cm^2/Vs. Different curves corresponds to the following parameters: (1): $n_{QW} = 2\ 10^{12}$ cm^{-2}, L_{QW} = 2 nm; (2): $n_{QW} = 2\ 10^{13}$ cm^{-2}, L_{QW} = 2 nm; (3): $n_{QW} = 2\ 10^{13}$ cm^{-2}, L_{QW} = 4 nm;

Currently, p-doped nitride multiple quantum wells and superlattices are fabricated for different Al-fractions, different thicknesses of the well and barrier layers, different Mg-doping, etc. This results in the following basic parameters of these structures: concentrations of two-dimensional holes are from 10^{12} cm^{-2} to 4 10^{13} cm^{-2} ; hole *lateral* mobilities are from 5 cm^2/Vs to 50 cm^2/Vs;barrier height from 100 meV to 400 meV depending on Al-fraction and superlattice period.

For typical parameters of quantum wells composing p-doped superlattices, the results of calculation of hole heating in the lateral electric field are presented in Fig. 2 for the *nitrogen* temperature. Because of relatively small mobility and strong hole-optical phonon coupling, hole heating is actual at large fields of about, or above 10 kV/cm. For example, at the field 20 kV/cm the hole temperature is twice of that at the absent of the field. The drift velocity is about several units of 10^6 cm/s and tends to saturation in high fields. For room temperature we found much less heating effect at the fields below 100 kV/cm.



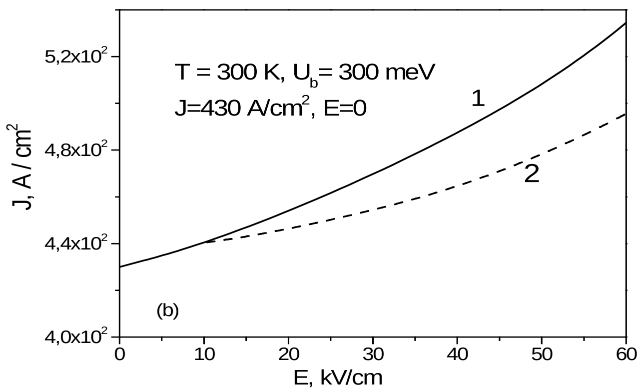


Fig. 3. Density of the hole injection current per a single quantum well. The barrier heights and the current densities in the absence of the field are indicated. (a): The nitrogen temperature, curves 1,2,3 correspond to the case indicated in Fig. 2; (b): The room temperature, L_{QW} = 2 nm, n_{QW} = 3 10^{13} cm^{-2} , curves 1 and 2 are for μ=30 cm^2/Vs and μ=10 cm^2/Vs, respectively.

The hole injection currents induced by lateral field heating are illustrated in Fig. 3 for a single quantum well. At low (nitrogen) temperature the effect is large: the hole current increases by many order of value and reaches tens of A/cm^2 at fields above 10 kV/cm. As well established, critical (threshold) current densities for UV laser generation in the nitrides are of several kA/cm^2 [1-3]. From the results presented in Fig. 3, it is followed that in the superlattices with 10 to 50 quantum wells, the critical current can be reached with the help of hole heating.

At room temperature, for heavy doped superlattices with the barriers below 200 meV the free hole concentrations are large enough to provide necessary injection currents. For larger barriers, the heating effect on the hole current is observable, but the hole current enhancement is much smaller that that of the low temperature, as seen in Fig. 3. (b) for barrier height 300 meV.

In the emitters with larger content of Al or thicker layers, heights of the barriers can be larger [13] and the heating effect is to be more pronounced even at room temperature. In Fig. 4, we show the results obtained for U_b = 400 meV and U_b = 500 meV. These results indicate that exploiting the hot-hole injector on the base of multilayered superlattices, one can reach more efficient pumping of nitride structures with large Al content to go deep into UV spectral range.

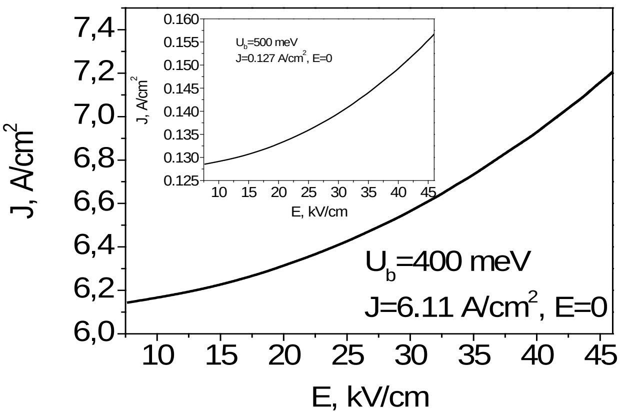


Fig. 4. The same as in Fig. 3 for T=300 K, L_{QW} = 3 nm, n_{QW} =3 10^{13} cm^{-2} , and barrier heights 400 meV and 500 meV.

As followed from the above analysis, to reach heating of “slow” holes, one should realize lateral electric fields above 10 kV/cm. Assuming that lateral V_{SD} voltage is not higher than 10 V, we obtain an estimate for the source-drain intercontact distance: it should be from 1 μ to 5 μ. Source/drain contacts to superlattices with such intercontact distances can be fabricated by different methods of the contemporary technology.

The use of a system S-D-S-…-D-S-D of lateral contacts to p-doped superlattices provides *the multiple hot-hole injector*. This contact system is illustrated in Fig. 5. The multiple hot-hole injector will provide hole injection to the active region of light emitting devices with a large cross section.

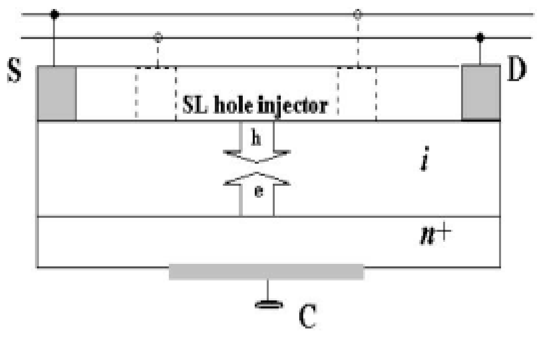


Fig. 5. Schematics of multiple hole injector.

Testing the hot-hole injector by using III-V compound emitting devices. The idea of the hot-hole injector can be tested by using a *p*-doped III-V compound superlattice, since for the latter the technique of growth and contact providing are much more developed. Another advantage of testing the idea on III-V compound devices is much higher hole mobility, which increases maximal acceptable intercontact distance to above 10 μ. Besides, the hot-hole injector can be used for some specific applications of III-V electronics and optoelectronics, when additional control of the hole injection is necessary.

Other uses. Proposed hot-hole injector can be used also to solve the low-acceptor activation problem in other bipolar devices based on wide gap materials. Particularly, it can improve hole injection in bipolar wide band-gap devices like bipolar transistors, thyristors, etc.

In summary, the proposed method introduces a new active element for short-wavelength light emitting devices to enhance hole injection currents. This converts the present two-terminal wide band-gap material based devices into three terminal devices. The method allows to solve the problem of low acceptor activation in wide gap semiconductor materials. Particularly, the method is applicable for the nitride heterostructures with a large Al-fraction to expand the spectrum of emitted light to deep UV range. By using the hot-hole effect, low temperature UV emitters with enhanced hole injection can be fabricated. Besides, the hole injector can perform an important controlling function by modulation of the injection current and light emission through alternative source-drain voltage. Contemporary heterostructure technology allows to integrate multiple injectors into a single mictochip and to control current distribution and light emission in active region of the device with a large cross section.

Nitride based lateral current pumped emitter (LACE).

As discussed above, in a p-doped superlattice the average hole concentration can be onsiderably enhanced due to high activation efficiency of in-barrier acceptors that supply the holes into quantum wells. However, the holes, however, are mostly confined inside the wells. The potential barriers that separate the wells can be as high as 100-400 meV. These barriers hinder participation of the holes in the *vertical transport* typical for standard light-emitting devices. In the project, we propose to utilize the *lateral transport* of holes and electrons confined in group-III nitride quantum wells and superlattices for high-intensity light emission.

The proposed device structure. The main element of the proposed structures is a single quantum well schematically illustrated in Fig. 6. The quantum well layer is confined by selectively-doped barriers. Each barrier is doped laterally, so that an initial region doped with acceptors is followed by an undoped (intrinsic) region and, finally, by the region doped with donors. Thermal activation of the dopants in the barrier supplies carriers into the quantum well layer.

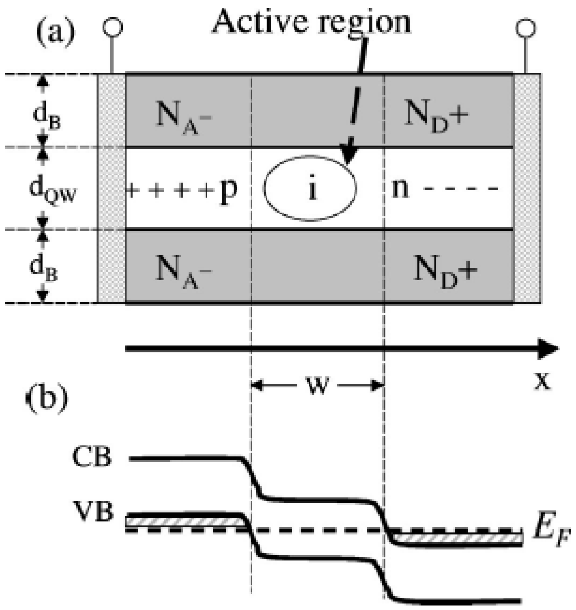


Fig. 6. (a): Schematic illustration of the proposed multilayered lateral *p-i-n* structure; (b): Energy band diagram in the lateral direction with no bias. CB and VB indicate the lowest populated energy levels in conduction and valence bands, respectively, E_F marks the Fermi level in unbiased structure.

Since the nitrides form type-I heterostructures, the quantum well layer accumulates both types of free carriers which lead to the formation of *lateral p-i-n structure*. Such *p-i-n* structures can be fabricated by using re-growth techniques [14], position-dependent implantation methods [15], etc. The contacts are to be made to *p-* and *n-* regions as illustrated in Fig.~6 (a). Similarly, latera*l p-i-n* structure on the base of a multiple quantum well system can be used.

The energy band diagram corresponding to an unbiased lateral *p-i-n* structure is shown in Fig. 6 (b). The energy barriers separating *p, i*, and *n* regions arise due to the formation of charged regions.

Although the band bending is similar to that of a *p-i-n* homostructure, the charge regions in a multilayered system are formed differently. Indeed, for a *p-i-n* homostructure the *local* charge neutrality takes place in the *p-* and *n-* regions and the uniformly charged (depletion) layers arise at the *p-i* and *i-n* junctions. In the planar multilayered structure, the barrier and quantum well layers are electrically charged in the doped regions. The quasi-neutrality occurs *on average* for any cross-section far from the junctions. For the cross-sections near the junctions, the average charge is not zero. This charge is responsible for the formation of potential barriers at the junctions. In a forward biased structure, the potential barriers decrease providing for an injection of confined holes and electrons into the *i*-region. This planar *double injection* gives rise to a non-equilibrium two-dimensional (2D) electron-hole plasma in the *i*-region. Radiative recombination of the plasma in the active region results in light emission. A superlattice arranged from quantum wells considered here will form an efficient source of radiation - LAteral Current pumped Emitter (LACE).

Description of lateral double injection. For the case of vertical transport, the theory of double injection in the *p-i-n*-homostructures and heterostructures is well developed (see Ref. [16]). It is based on a few well proven assumptions: (i) in electrically biased structures, the *p, i* and *n* regions are mostly quasi-neutral, and (ii) the charged (depleted) regions remain very narrow. The assumptions allow one to avoid a detailed description of the processes in the depletion regions. To expand this approach to lateral double injection, we need to analyze and compare the length scales characterizing the structure under consideration. These include different groups of the scales: the geometric scales - the quantum well layer thickness L_{QW}, the barrier layer thickness L_B, and the extension of the *i*-region *w*; the kinetic lengths - diffusion lengths of the electrons L_n, and holes L_p; and the lengths of screening of an electric charge by carriers $l_{sc}^{n,p}$. In light emitting devices the *i*-region should be extended: $w > L_n$, L_p, where the macroscopic diffusion lengths are of the order of micrometers, while the screening lengths l_{sc} are less than 10 nm [12]. Thus, we obtain the following inequalities:

$$w > L_n\ ,\ L_p > L_{QW}\ ,L_B\ > l_{sc}.$$

The lateral extensions of *p-i* and *i-n* junctions are estimated to be less than, or of the order of L_{QW}, L_B. Thus, the charged layers are very narrow and electron-hole recombination there can be neglected. These inequalities and conditions allow us to propose and use the following approach. The extended *i*-region can be considered as quasi-neutral with the carrier transport described by the bipolar drift-diffusion equations [16]. The lateral electric fields inside the *p-* and *n-* regions are expected to be negligible. In the narrow charged regions, we subject the equations to the relevant boundary conditions.

Under these assumption, the basic equations are as follows. Directing the x axis along the quantum well, we get:

$$dj_n/dx = dj_p/dx = - R\ ,$$

$$j_n = - \mu_n\, n\, E - D_n\, dn/dx\ ,\ j_n = - \mu_p\, p\, E - D_p\, dp/dx\ ,$$

where E is the electric field; n, p are the areal concentrations; j_n, j_p are the flux densities; μ_n , μ_n are the mobilities and D_n, D_p are the diffusion coefficients for the electrons and the holes, respectively; and R is the rate of recombination. We will label these parameters by the upper indices *p, i* and *n* for the respective regions. In the *i*- region, the quasi-neutrality condition yields:

$$E=\frac{J}{e(\mu_p^{(i)}+\mu_n^{(i)})p^{(i)}}+\frac{D_p^{(i)}-D_n^{(i)}}{(\mu_p^{(i)}+\mu_n^{(i)})p^{(i)}}\frac{dp^{(i)}}{dx},$$

where J is the electric current density calculated per quantum well. The boundary conditions for the above equations. are:

$$p^{(p)}=p_0,\ n^{(p)}=0 \text{ as } x\to-\infty;\ \ n^{(n)}=n_0,\ p^{(n)}=0 \text{ as } x\to+\infty;$$

The fluxes of minority carriers at the junctions are determined by the diffusion processes: $j_n = -D_n^{(p)}\, dn^{(p)}/d\,x$ at $x=0$ and $D_p^{(n)}\, dn^{(p)}/d\,x$ at $x=w$. At the *p-i* junction, the hole concentration from the *i-* side [$p^{(i)}(0)$ and the electron concentration from the *p-* side [$n^{(p)}(0)$] are determined by the energy barrier Δ_p (of the *p-i* junction) and the hole concentration p_0 in the - side of the structure:

$$p^{(i)}(0)=\frac{m_p k_B T}{\pi\hbar^2}\ln[1+e^{-\Delta_p/k_BT}(e^{\pi\hbar^2 p_0/k_BTm_p}-1)],$$

$$n^{(p)}(0)=\frac{m_n k_B T}{\pi\hbar^2}\ln[1+e^{-\Delta_p/k_BT}(e^{\pi\hbar^2 p^{(i)}(0)/k_BTm_n}-1)].$$

Here, $\hbar$ is the Planck constant, k_B is the Boltzmann constant, T is the temperature, m_n and m_p are the effective masses of electrons and holes, respectively.

Similarly, at the *i-n* junction the electron concentration from the i-side [\$$n^{(i)}$ (w)] and the hole concentration from the *n* side [$p^{(n)}$(w)] are determined by the energy barrier Δ_n (of the *i-n* junction) and n_0. The voltage drop across the structure V can be found as

$$eV=E_G+E_{Fp}+E_{Fn}-\Delta_p-\Delta_n-e\int_0^w E\,dx,$$

where E_G is the energy spacing between the electron and hole subbands in the quantum wells, $E_{F\,p}= k_B\ T\ ln\ [\ exp(\pi\hbar^{\ 2}\ p_0/m_p\ k_B\ T) - 1]$ is the Fermi level of the holes in the *p-* side of the device, and E_{Fn} has the same meaning for the electrons in the *n-* side and can be calculated similarly.

Parameters of bi polar pl asma unde r l ateral double i njection i n qu antum w ells. Formulated equations completely describes the problem of a lateral *p-i-n* structure under electric bias and allow us to calculate basic parameters necessary to estimate nonequilibrium electron-hole concentrations, formation of population inversion and UV light gain in the proposed structure.

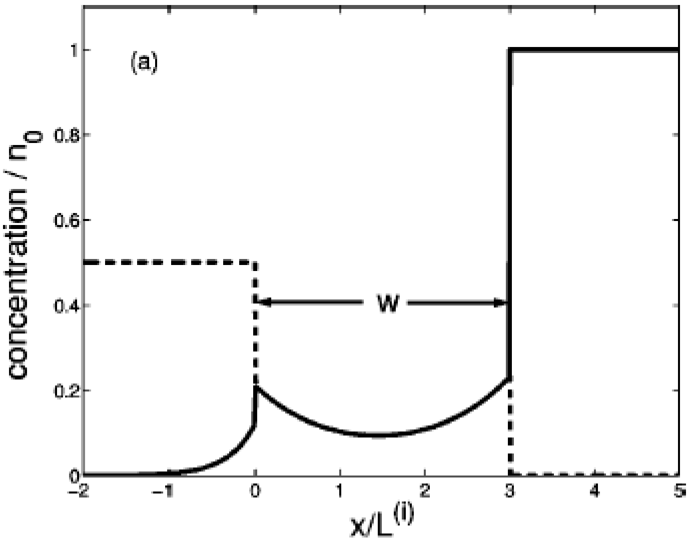


Fig. 7. Concentrations of the electrons and hole vs distance x along the lateral *p-i-n*structure based on GaN quantum well. The depletion region thicknesses are neglected. T=80 K. The doped concentrations are $p_0 = n_0/2 = 5\ 10^{12}\ cm^2$. The concentrations are in units n_0. The hole concentrations is given by the dashed line, the electron concentration is given by the full line. In the quasi-neutral region both concentrations are equal.

Let us consider a GaN/AlGaN lateral *p-i-n* structure. Assuming the linear recombination mechanism with the recombination time τ_R different in the different device regions, we set $\tau_R^{(p)} = \tau_R^{(p)} = \tau_R^{(n)} = 0.1$ *ns*, $\tau_R^{(i)} = 1$ *ns* [2], $\mu_n/\mu_p = 20$, $\mu_n = 500\ cm^2/sV$ [13], $m_n = 0.18\ m_0$, and $m_p = 0.8\ m_0$, where m_0 is the free electron mass. For $T = 80K$, this results in the ambipolar diffusion length $L^{(i)} = 1.2\ \mu m$, and diffusion lengths $L_n^{(p)} = 1.7\ \mu m$ and $L_p^{(n)} = 0.4\ \mu m$. In Fig. 7 we present the distribution of the electrons and holes injected into the *p-i-n* structure obtained for the *i*-region of extension w =3.6 μm and two dimensional concentrations of the electrons and holes in *n-* and *p-* regions $n_0 = 10^{13}$ cm^{-2} and $p_0 = 5\ 10^{12}$ cm^{-2}, respectively. The current density (per unit length of the second lateral dimension) is $J = 16\ mA/mm$. In the quasi-neutral region, the concentrations are nonmonotonic with a maximum p_M at the *n-i* junction and a minimum p_m at the middle of this region. The corresponding energy diagram is shown in Fig. 8. One can see, that the potential barriers at the junctions Δ_p and Δ_n are finite and decrease with increasing with the current. For example, the *p-i* junction barrier vanishes first at $J = 188\ mA/mm$. The built-in potential related to the diffusion field facilitates spreading of 'slow' holes through the extended *i*-region. The total voltage drop across the *p-i-n* structure with 5-nm quantum wells is *4.22 V*.

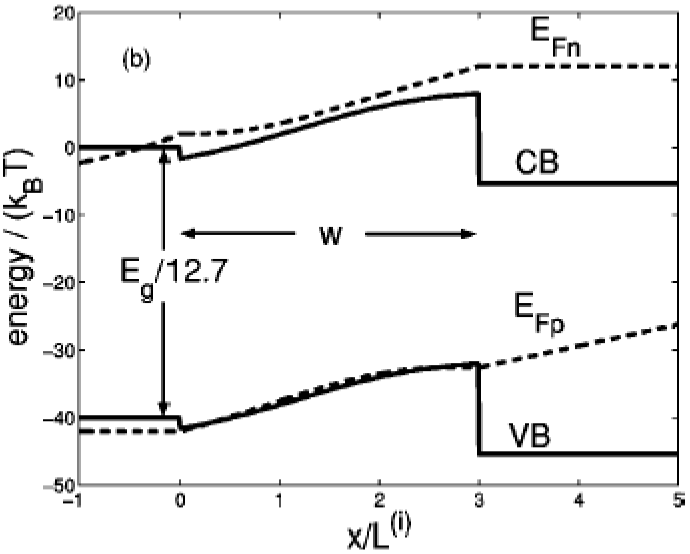


Fig. 8. The energy band diagram of the structure calculated in Fig. 7. CB and VB indicate the lowest populated energy levels in conduction and valence bands, respectively. Quasi-Fermi levels for the electrons and holes are shown.

Parameters characterizing the lateral injection in other nitride based *p-i-n* structures are collected in Table 1. There we present the results at given electric current densities and for different temperatures, and different doping of the *p-* and *n*-sides of the structures. One can see that there is always a voltage drop across the *i*-region (of about 100…250 meV). Strict “flat band conditions” are not realized for all analyzed regimes. Thus the built-in electric “stimulates” drift of ‘slow’ holes across the *i*-region. The nonequilibrium plasma concentrations significantly (by factor 2..3) change across the *i-* region. The double injection can provide the plasma concentrations from 10^{12} cm^{-2} to 10^{13} cm^{-2} depending on doping of the *p-, n* -sides of the structures. The larger concentrations require larger currents. Typical current densities vary from tens to hundreds mA/mm.

We can conclude this part of research by statement that double injection effect in lateral *p-i-n* structures is significant and can provide high concentrations of nonequilibrium electrons and holes at relatively modest electric currents through these structures..

Table 1. Parameters characterizing the lateral injection in the nitride based *p-i-n* structures with (a): $p_0 = n_0/2 = 5\ 10^{12}$ cm^{-2}; (b): $p_0 = n_0 = 10^{13}$ cm^{-2}; (c): $p_0 = n_0 = 2\ 10^{13}$ cm^{-2}; (d): $p_0 = n_0 = 4\ 10^{13}$ cm^{-2}. U/e is the voltage drop across the quasi-neutral region.

QW Material	T K	J mA/mm	Δ_p	Δ_n meV	U	p_m 10^{12}	p_M cm^{-2}
GaN							
(a)	80	16	11	92	66.6	0.9	2.3
(b)	250	80	20	42	284	2	6
(c)	300	110	46	138		3.5	8
(d)	300	220	78	250	250	6.8	15
InN							
(a)	80	37	12	153	74	1	2.9
(b)	250	88	33	130	210	1.6	4
(b)	300	110	27	73	285	2.4	6.6

Light a mplification fo r n itride h eterostructures. To estimate threshold conditions of the population inversion and amplification coefficient in the nitrides lateral *p-i-n* structures, we have conducted the following studies: (i) Quantization of the electrons and holes in quantum wells, including detailed calculations of hole subbands in quantum wells. (ii) Calculation of the matrix elements for band-to-band photo-transitions. (iii) Determination of optical gain/loss as a function of structure parameters, electron and hole concentrations, temperature and light wavelength.

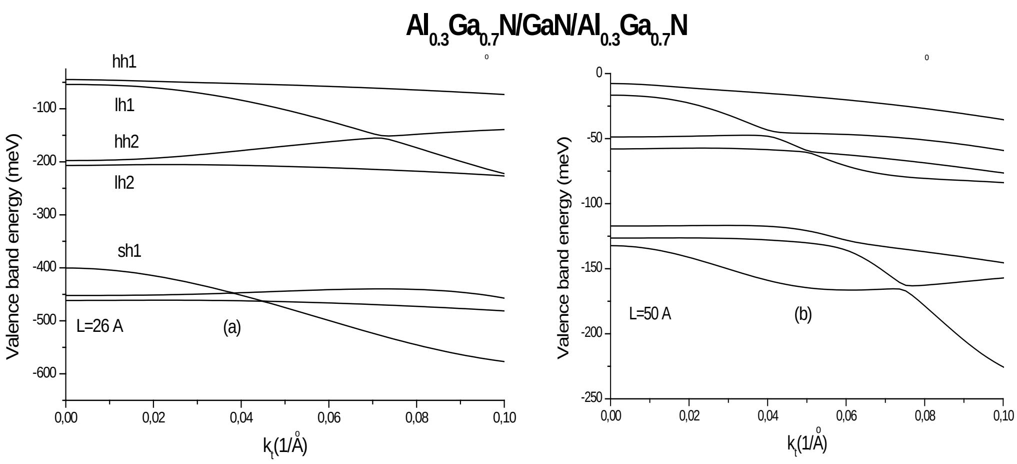


Fig. 9. The valence subband structure calculated for strained $Al_{03}Ga_{07}N/GaN/\ Al_{03}Ga_{07}N$ quantum wells for two well widths: (a): 26 A^0 and (b): 50 A^0. It is shown the upper subbands hh1, lh1, hh2, lh2, sh1, etc.

For quantization of the holes in nitride quantum wells we used the Rashba-Sheka-Pikus matrix Hamiltonian for coupled G_9, G_7 and G_7 levels (see, for example Ref. [17]. Parameters for this Hamiltonian we used from Ref. [18]. The electrons were quantized with the use of assumption of a simple parabolic zone with the effective mass from [17]. In Fig. 9, we show the valence subband structure for quantum wells of two thicknesses for 7 lowest hole subbands. Obviously, the thick quantum well demonstrates closer spacing between the subbands.Note, that for farther calculations of photo-transitions only two-three valence subbands are important with contribution of an extended interval of the lateral wavevector k_t.

For highly anisotropic wurtzite strained structures, photo-transitions depend strongly on light polarization. We found that for the upper few valence *lh* and *hh* subbands the dominant photo-transitions correspond to *TE* light polarization. Found matrix elements for this type of the photo-transitions from the lowest conduction subband c1 are presemted in Fig. 10 for the strained quantim well of thickness 26 A_0. The relatively fast changes in the matrix elements strictly correspond to pseudo-crossing o different branches of the hole dispersion.

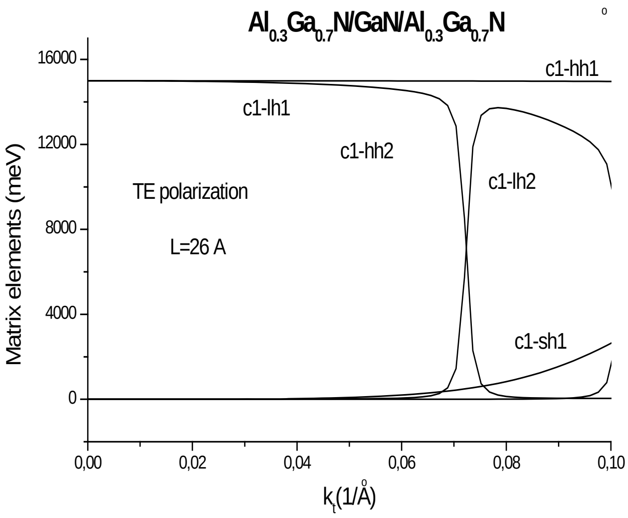


Fig. 10. The matrix elements for photo-transitions between the lowest electron subband (c1) and upper hole subbands (hh1, hh2, lh1, lh2 and sh1) at *TE* polarization.

Obtained results for the electron and hole energy subbands and the matrix elements of interband photo-transitions allowed us the calculate the light amplification coefficient. The amplification coefficient α can be expressed through the optical confined factor Γ and parameter α_0 determining contribution a single quantum well:

$$\alpha = \alpha_0 \Gamma.$$

The optical confined factor Γ depends on particular optical resonator design and can reach the magnitude of about 0.1…0.01 [12]. The "specific amplification" of α_0 can be directly calculated. If the structure is given, α_0 depends on the ambient temperature and electron-hole plasma concentrations. In Fig. 11 we present the energy dependence of the specific amplification $\alpha_0 /100$ for 26 A^0 quantum well at the nitrogen temperature. That is presented numbers are presented amplification for relatively low optical confined factor $\Gamma=0.01$. The plasma concentrations are varied in wide interval from 10^{12} cm^{-2} to 10^{13} cm^{-2}. We may conclude that the threshold concentration necessary to form population inversion for $T=77\,K$ is $n = p \approx 1.5\ 10^{12}$ cm^{-2}. As for the magnitude of the amplification coefficient, at this temperature it is large. For example, at $n=p=2\ 10^{12}\ cm^{-2}$ we found $\alpha_0/100 = 22\ cm^{-1}$ and $\hbar\omega\text{-}E_g = 6.5\ meV$, at $n=p=5\ 10^{12}\ cm^{-2}$ we found $\alpha_0/100 = 110\ cm^{-1}$ and $\hbar\omega\text{-}E_g = 20\ meV$.

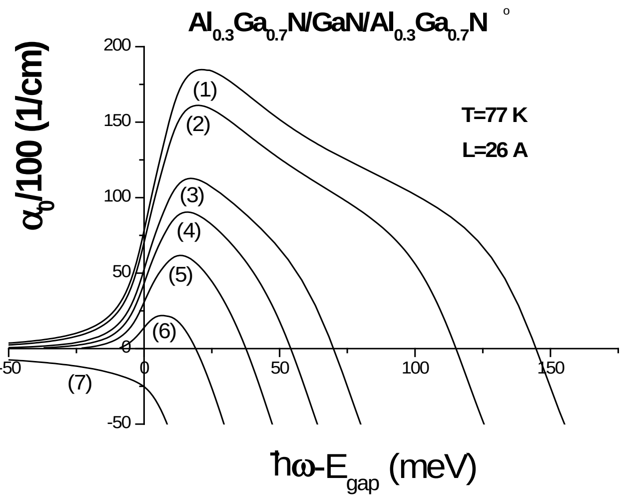


Fig. 11. Specific amplification for a single quantum well of thickness 26 A^0 at the nitrogen temperature. The curves *1* through *7* corresponds to plasma concentrations 10^{13} cm^{-2}, 8 $10^{12}cm^{-2}$, 5 10^{12} cm^{-2}, 4 10^{12} cm^{-2}, 3 10^{12} cm^{-2}, 2 10^{12} cm^{-2} and 10^{12} cm^{-2}.

In Fig. 12 we present similar calculations for room temperature. One of the effect of increasing the temperature is an increase in the threshold plasma concentration: population inversion and amplification arise at concentrations above 4 10^{12} cm^{-2} . Another effect is a considerable decrease in the magnitude of the amplification. For example, at $n=p=5\ 10^{12}\ cm^{-2}$ we found $\alpha_0/100 = 9\ cm^{-1}$ and $\hbar\omega-E_g = 11\ meV$.

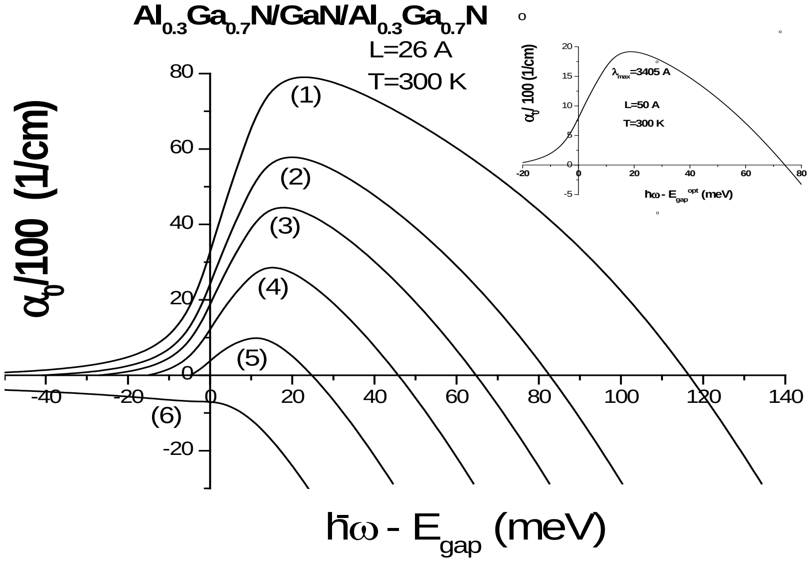


Fig. 12. The same as in Fig. 11 for room temperature. The curves *1* through 6 corresponds to plasma concentrations 10^{13} cm^{-2}, 8 $10^{12}cm^{-2}$, 7 10^{12} cm^{-2}, 6 10^{12} cm^{-2}, 5 10^{12} cm^{-2} and 4 10^{12} cm^{-2}. In the inset: the amplification for 50 A^0 GaN quantum well at the room temperature and concentration 8 $10^{12}cm^{-2}$.

Similar results are obtained for the quantum wells of 50 A^0 -thickness, as illustrated by the inset of Fig. 12. For larger quantum well the magnitude of $\alpha_0/100$ is less approximately by factor 2..3. However, we have to remember that for the same optical resonator the optical confinement factor Γ is greater for the larger well by factor 2.

Now we can combine the data collected in Table I and in Figs. 11-14. The data allow one to conclude that under the planar double injection, high densities of electron-hole plasma well above 10^{12} cm^{-2} can be achieved. Our calculations show that under lateral injection, the interband

population inversion occurs for all cases presented in Table I. For almost all cases light amplification takes place across the entire i region.
The population inversion can be reached at quite modest currents and biases. For instance, in a GaN-based lateral current pumped emitter with ten QWs, a strip of area of 100 ^{x} 3.6 μm^2 can be inverted with currents less than 16 mA at 80 K. At that, net light amplification will be about 4 even in the case of the optical confined factor 0.01.
At room temperature, it is necessary to use the lateral *p-i-n* structures with higher doping (above 10^{13} cm^{-2}). However, and for this case light amplification is large and optimization in the optical confinement factor will lead to modest threshold current for laser generation (1..2 A for 10 quantum wells).
For 50 A^0 quantum wells, the radiative recombination of the plasma will produce light emission centered at ≈340 and 587 nm for GaN and InN QWs, respectively; the wavelength can be scaled to the deep-ultraviolet range by using AlGaN or AlGaInN lateral current pumped emitter.

Concluding this task, we can state that contemporary group-III nitride technology allows fabrication of structures for light emitters, laterally, selectively doped quantum wells and superlattices. In such structures, planar p-i-n regions with high concentrations of two-dimensional electrons and holes are formed and highly efficient double injection occurs when a bias is applied along the quantum wells. This results in high densities of two-dimensional electron-hole plasma in an extended *i*-region and population inversion of the conduction and valence bands. The planar double injection that occurs in lateral current pumped emitters is an efficient method to solve the problem of low acceptor activation in the nitrides and to realize electrical pumping of short-wavelength nitride-based lasers.

High-field transport for rare-earth doped nitride electroluminescent devices.
Electroluminescence effect of the trivalent rare-earth ions occurs due to electron impact excitation. Typical electric fields for the effect are in the range from hundreds of kV/cm to MV/cm. Thus namely high-field transport regime is of primary importance for this type of the electroluminescent devices. The group III-nitrides present a class of materials demonstrating unique properties of high-field transport ans can be used for fabrication of the electroluminescent devices [1]. Particularly, the large energy separation between the lowest Γ-minimum and the side valleys allows carriers to reach developed the so-called runaway effect, which is characterized by high electron energy, and use the hot electron transport regimes with energy sufficient to excite rare-earth dopants [19].
Studying the high field transport in the nitrides we found the set of characteristic parameters for hot electrons in the nitrides. They are estimated in Table 2. There we present the characteristic length and time of the energy loss l_O and τ_O, the field necessary to gain large energy F_O and corresponding drift velocity V_O. For comparison we present also the parameters for GaAs. One can see that electron transport is always highly dissipative. To reach electrons with energy necessary for excitation of rare-earth electroluminescence the most appropriate are the transient

Table 2. Relevant material parameters for hot electrons in the nitrides.

Material	$l_O(\AA)$	τ_O(ps)	$F_O(kV/cm)$	$V_O(10^7\ cm/s)$
InN	90	0.04	99	2.65
GaN	35	0.018	257	2
AlN	12	0.01	828	1.35
GaAs	525	0.26	6.9	2.3

transport regimes. For steady state and quasi-steady state conditions these regimes can be realized in ultra-short nitride diodes. Under the transient transport regime one can reach hot electron energy of the order of 1 eV.

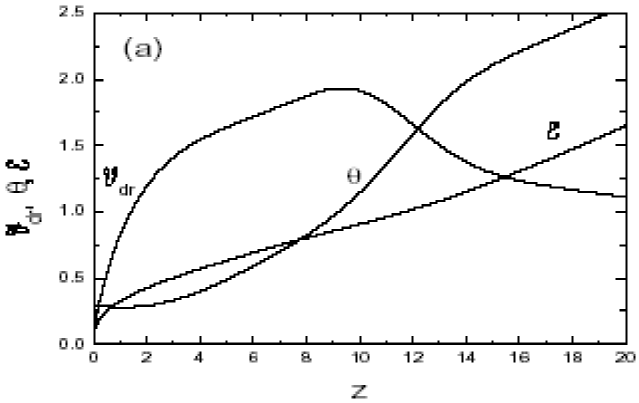


Fig. 13. Characteristic dimensionless drift velocity, electron temperature and local electric field $v_{dr}(z)$, $\theta(z)$, and $\varepsilon(z)$ for spatially dependent transport in nitride short diodes at a given current density 1.1 kA/cm^2. The parameters $v_{dr}(z)$ and $\varepsilon(z)$ are scaled to V_O and F_O given in Table 2. The electron temperature $\theta(z)$ is scaled to the ioptical phonon energy (≈92 meV≈ 1060 K for GaN). The coordinate z is measured in units l_O.

For transient transport in short devices the space charge effects should be taken into account. In Fig. 13, we show the results of calculations of space charge limited transport in the diode of the 70 nm length. For this example, after acceleration in the diode, the electrons are characterized by the temperature ≈3000 K, their average energy is ≈ 0.5 eV despite very modest current density ≈1.1 kA/cm^2 and the total voltage drop ≈ 1.9 V. Hot electrons with so large electron temperature are capable to excite the lowest energy levels of Er^{3+} with energy 0.8 eV ($^4I_{3/3}$ states). Note, the local electric fields predicted for this case are below 450 kV/cm, i.e., no electric breakdown is expected.

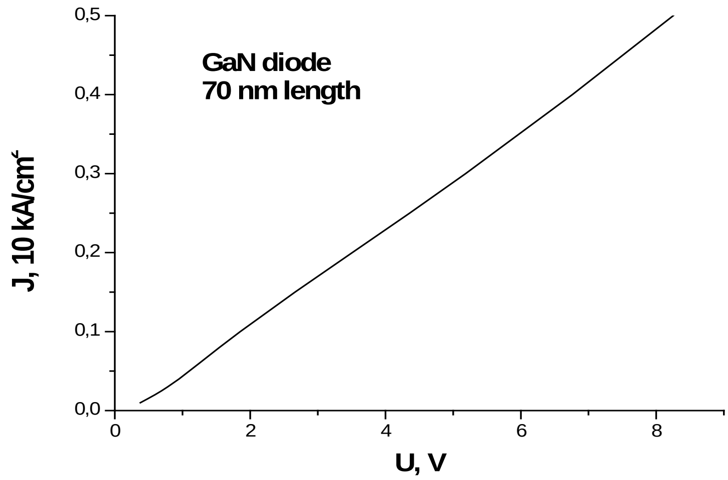


Fig. 14. The I-V curve for a short GaN diode with charge limited transport of hot electrons.

Using the results on hot electrons in short nitride samples we can suggest that efficient electroluminescent erbium doped device should consists of an accelerating base of several hundreds of nanometers followed by a 5…10 nm rare-earth doped layer. The electrons gain the energy in the accelerating base and then enter the doped layer and excite rare-earth dopants. The concentration of the excited dopants N^* can be estimated through the current density J:

$$N^* = \sigma\tau J N / e [1+ \sigma\tau J/e],$$

where σ is the excitation cross-section, τ is the relaxation time, e is the elementary charge and N is the dopant concentration. As the current J increases, the magnitude of N^* saturates: $N^* \approx N$. The saturation current is $J_{sat} = e/ \sigma\tau$. Typical magnitude of the parameters $\sigma\tau$ for Er^{3+} is from 10^{-21} cm^2s to 10^{-22} cm^2s. According to presented formula the saturation current density is estimated to be 0.1..1 kA/cm^2 . As it follows from Fig. 14, in short nitride diodes the necessary magnitudes of the hot electron current density are readily reached. Thus, the system based on the nitrides with Er^{3+} doped narrow layer can be used for efficient excitation of the electroluminescence in the important spectral region centered around 1.54 μm. The described device consists of four layers: n^+ -cathode, n (or i) accelerating base, Er^{3+} doped layer and finally n^+ anode layer. This set of the layers can be repeated like a cascade to increase light emission.

Concluding this task, we found that properly designed nitride structures can provide electron transport regimes with extremely hot electrons and high currents, both are necessary to excite efficient electroluminescence of Er^{3+} doped layers.

Implementation of the results. During the course of the first phase of this project, the working relations with US Army Research Office (Research Triangle Park, NC, USA) have been established. The results on enhancement of injection hole current were discussed with Dr. J. M. Zavada from the Electronic division of ARO. Particularly, the PI of this project, Prof. V. A. Kochelap discussed in detail the following topics important for result implementation for the Army:

- (i) main requirements for fabrication of the hot-hole injector structures;
- (ii) measurement and testing the hot-hole injector;
- (iii) fabrication of structures for lateral double injection.

Besides, applications of the results to wide gap materials was also discussed with group of Prof. K. W. Kim, who closely collaborates with US ARO in the field of UV optoelectronics.

List of publications:

The basic obtained results were discussed on several international conferences and described in several papers and reports. The support by the European Research Office and Army Research Office is acknowledged.

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Appendix-1

APPLIED PHYSICS LETTERS VOLUME 81, NUMBER 24 9 DECEMBER 2002

Laterally doped heterostructures for III–N lasing devices

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(Received 22 April 2002; accepted 16 October 2002)

To achieve a high-density electron-hole plasma in group-III nitrides for efficient light emission, we propose a planar two-dimensional (2D) p-i-n structure that can be formed in the quantum well layers due to efficient activation of donors and acceptors in the laterally, selectively doped barriers. We show that strongly nonequilibrium 2D electron-hole plasma with density above 10^{12} cm^{-2} can be realized in the i region of the laterally biased p-i-n structure, enabling the formation of interband population inversion and stimulated emission from such a lateral current pumped emitter (LACE). We suggest that implementation of the lateral p-i-n structures provides an efficient way of utilizing potential-profile-enhanced doping of superlattices and quantum wells for electric pumping of nitride-based lasers. [DOI: 10.1063/1.1527985]

Currently AlGaN and InAlGaN based heterostructures are of great interest for light-emitting diodes (LEDs), laser diodes (LDs), and photodetectors operating with radiation that covers the spectral range from green to deep ultraviolet.[1–3] Development of light emitting devices in this spectral range is stimulated by a number of practically important tasks including highly efficient lighting, high-density optical storage, stimulation of chemical processes, biomedical applications, etc. Pumped by the electrical current, blue LDs and green-blue LEDs have been realized in InGaN/InAlN structures and are commercially available.[4] Efficient UV electroluminescence of AlGaN has also been observed recently.[5]

Further improvement in the performance of group-III nitride based optoelectronics requires obtaining high-density hole currents in bipolar structures. It is well established that the difficulties in achieving high hole concentrations mostly come from the deep energy levels of known acceptors.[2,3,6,7]

It has been shown[6,8,9] that in a p-doped superlattice (SL), the average hole concentration can be considerably enhanced due to high activation efficiency of in-barrier acceptors that supply the holes into quantum wells (QWs). The holes, however, are mostly confined inside the QWs where their concentrations can exceed 10^{13} cm^{-2}.[9] The potential barriers that separate the QWs can be as high as 100–400 meV. These barriers hinder participation of the holes in *the vertical transport* typical for standard light-emitting devices. In this letter, we propose to utilize *the lateral transport* of holes and electrons confined in group-III nitride QWs and SLs for high-intensity light emission.[10]

The main element of the proposed structures is a single QW schematically illustrated in Fig. 1. The QW layer is confined by selectively doped barriers. Each barrier is doped laterally, so that an initial region doped with acceptors is followed by an undoped (intrinsic) region and, finally, by the region doped with donors. Thermal activation of the dopants in the barrier supplies carriers into the QW layer. Since the nitrides form type-I heterostructures, the QW layer accumulates both types of free carriers which lead to the formation of lateral p-i-n structure. Such p-i-n structures can be fabricated by using regrowth techniques,[11] position-dependent implantation methods,[12] etc. The contacts are to be made to p and n regions as illustrated in Fig. 1(a).

The energy band diagram corresponding to an unbiased lateral p-i-n structure is shown in Fig. 1(b). The energy barriers separating p, i, and n regions arise due to the for-

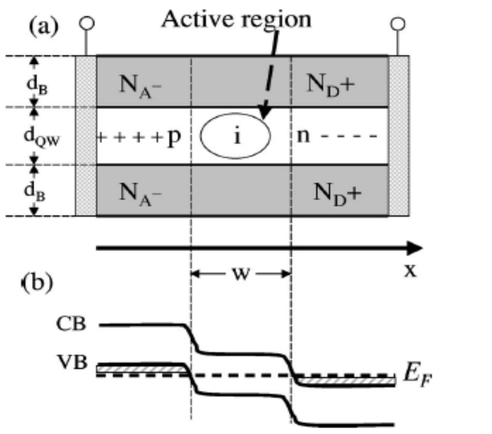

FIG. 1. Schematic illustration of (a) the proposed multilayered lateral p-i-n structure and (b) energy band diagram in the lateral direction with no bias. CB and VB indicate the lowest populated energy levels in conduction and valence bands, respectively.

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Apendix-2

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Solid-State Electronics 47 (2003) 169–171

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Short Communication

Enhancement of hole injection for nitride-based light-emitting devices

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Received 27 June 2002; accepted 15 July 2002

Abstract

A novel device design is proposed for a strong enhancement of hole injection current in nitride-based light-emitting heterostructures. Preliminary calculations show orders of magnitude increase in injected hole current when using the proposed superlattice hole injector device based on the real-space transfer concept.

Keywords: UV emitter; Group-III nitride; Enhanced hole concentration; Hole injection; Superlattice

1. Introduction

Further development of group-III-nitride based optoelectronics requires solution of a crucially important problem—obtaining highly doped p-type regions, or more precisely, high-density hole currents. It is well established that the difficulties in achieving high hole concentrations originate from (a) the relatively low solubility of the typical acceptors (Mg, Zn, C, etc.), (b) neutralization of these acceptors by formation of complexes with hydrogen and other material defects, and (c) most importantly, the deep level of known acceptors (about 250 meV for Mg in GaN [1]). Fabrication of heavily p-doped device regions is even more difficult to achieve for AlGaN materials, where energies of the accepter levels are found to be larger [1,2]. To overcome the low acceptor activation problem, it was suggested [3] that a p-doped ternary compound material with a spatially modulated chemical composition (e.g., a superlattice (SL)) can enhance the average hole concentration. Calculations [3] and Hall measurements [4,5] support the idea of improved acceptor efficiency in Mg-doped ternary SLs: the average hole concentration can be increased up to one order of magnitude. However, the main drawback of this approach is that the most of the holes ionized from the acceptors are localized inside the quantum wells (QWs), which have potential barriers as high as 100–400 meV. These barriers hinder participation of the holes in vertical transport required in typical light-emitting devices.

2. Proposed approach

To increase the overbarrier hole concentration and the vertical hole current, we propose a two-terminal hole injector schematically illustrated in Fig. 1(a). The injector consists of a p-doped SL base and two contacts S and D. The injector is separated from the rest of the device by an i-region. A bias voltage applied between the S and D contacts provides *lateral* hole acceleration and increases the effective temperature of the holes T_h, resulting in an enhancement of overbarrier hot-hole concentration. This is known as the real-space transfer effect [6].

In general, a light-emitting device can be thought of as a *three terminal device or light emitting triode (LET)*, schematically shown in Fig. 1(b), with a hole-injector

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PII: S0038-1101(02)00314-3

Appendix-3:
29th ISCS, Lausanne (2002)

Efficient Nitride-Based Short-Wavelength Emitters with Enhanced Hole Injection

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Further progress in III-N based UV emitters requires solution of an important problem – obtaining high-density hole currents. The difficulties in achieving high hole concentrations mainly originate from high values of activation energy of known acceptors (about 250 meV for Mg in GaN). Use of Al-contained compounds leads to further increase in acceptor activation energy. To overcome *the low acceptor activation problem*, it was suggested [1] that the average hole concentration can be enhanced in p-doped ternary compounds with a spatially modulated chemical composition [e.g., a superlattice (SL)]. Calculations [1] and measurements [2] show an improved acceptor efficiency in Mg-doped SLs: the average hole concentration can be increased up to one order of magnitude. Nevertheless, most of the holes ionized from the acceptors are localized inside the quantum wells (QWs) with the potential barriers as high as 100-400 meV. These barriers hinder participation of the holes in vertical transport required in traditional light-emitting devices. In this report we propose two novel solutions to enhance hole injection in wide gap semiconductors.

Low-intensity (non-coherent) emitters: To increase the overbarrier hole concentration and the vertical hole current, we propose to modify the traditional design of LEDs by introducing a two-terminal hole injector schematically illustrated in Fig. 1(a). The injector consists of a *p*-doped SL base and two contacts S and D. The injector is separated from the rest of the device by an *i*-region. A bias voltage applied between the S and D contacts provides *lateral* hole acceleration and increases the effective temperature of the holes T_h. An increase in T_h will result in significant enhancement of overbarrier hot-hole concentration. This is known as the real-space transfer effect [3]. The proposed device can be thought of as a *three terminal device, or light-emitting triode (LET)* schematically shown in Fig. 1(b), with a hole-injector region, an intrinsic *i*-layer, and an *n*-doped region (contact C). If a *p*-doped SL is used as a hot-hole injector, the device can operate as a charge injection transistor [4].

Appendix-4:
2002 MRS Fall Meeting

WIDE BAND-GAP LIGHT EMITTERS WITH IMPROVED HOLE INJECTION

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For group-III nitride materials the difficulties in achieving high hole concentrations originate from high values of activation energy of acceptors. The average hole concentration can be increased in p-doped ternary-nitride superlattice (SL). However, most of the holes ionized from the acceptors are localized inside the quantum wells (QWs) and the potential barriers hinder participation of the holes in vertical transport required in traditional light-emitting devices (LEDs). In this report we propose two novel solutions to enhance hole injection in wide band-gap LEDs by using p-doped SLs.
Low-intensity emitters: The conventional LEDs can be modified by introducing a two-terminal hole injector, which consists of a *p*-doped SL base and two contacts S and D. A bias voltage applied between the S and D contacts provides *lateral* hole acceleration and increases the effective temperature of the holes. This results in significant enhancement of overbarrier hot-hole concentration. The proposed LED can be thought of as a *three terminal device,* where the hot-hole SL-injector is placed on the top of heterostructure with an intrinsic *i*-layer, and an *n*-doped region contacted to the cathode C. If contact D is grounded, a positive voltage is applied to contact S, and a negative bias is applied to the cathode C, the double injection into i-region occurs: enhanced hot-hole njection from the SL and the electron injection from the n-region. In the report we discuss parameters of the nitride-based hot-hole injectors and characteristics of the three terminal UV-LEDs.
High-intensity lateral current pumped emitters (LACE): To achieve high-density electron-hole plasma (EHP) and interband population inversion in group-III nitrides, we propose a planar *p-i-n* structure created in selectively-doped SLs: a region doped with acceptors is followed in lateral direction by an undoped i-region and, finally, by the region doped with donors. Thermal activation of the dopants supplies carriers into the QW layers. The QW layers accumulate both types of free carriers which leads to the formation of a *lateral p-i-n* structure. When a forward bias is applied to the lateral *p-i-n* structure, the planar double injection gives rise to non-equilibrium 2D EHP in the *i*-region. As an example, consider the lateral structure with 5 nm QWs, 3.6 μm i-region extension and 2D-carrier concentrations in *p-* and *n*-regions equal to 5 10^{12} cm^{-2}, the ambient temperature is 80 K. For InN QWs we found that at the current density 37 mA/mm (per a single QW) the EHP concentration in the i-region reaches magnitudes of $(1-3)\times10^{12}$ cm^{-2}. The population inversion for photo-transitions centered at the wavelength λ=587 nm occurs across the entire i-region. For GaN QWs we found similar EHP concentrations at the currents density above 16 mA/mm, the population inversion occurs for λ=344 nm. For the latter case with ten QWs, a strip of area of 100×3.6 μm^2 can be inverted in the currents less than 16 mA and the total voltage drop across the structure 4.22 V, i.e., the population inversion can be reached at modest currents and biases.

Appendix-5:

Title:	**QUASI-BALLISTIC AND OVERSHOOT TRANSPORT IN GROUP III-NITRIDES**

DOI No: doi:10.1142/S0129156404002272

Source: International Journal of High Speed Electronics and Systems, Vol. 14, No. 1 (2004) 127-154

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Abstract: We analyze steady-state and transient electron transport in the group III-nitride materials at high and ultra-high electric fields for different electron concentration regimes. At high electron concentrations where the electron distribution function assumes a shifted Maxwellian, we investigate different time-dependent transient transport regimes through the phase-plane anyalysis. Unexpected electron heating pattern is observed during the velocity overshoot process with a moderate electron temperature near the peak velocity followed by rapid increase in the deceleration period. For short nitride diodes, space-charge limited transport is considered by taking into account the self-consistent field. In this case, the overshoot is weaker and the electron heating in the region of the peak velocity is greater than that found for time-dependent problem. The transient processes are extended to sufficiently larger distances as well. When the electron concentration is small, we propose a model which accounts the main features of injected electrons in a short device with high fields. The electron velocity distribution over the device is found as a function of the field. It is demonstrated that in high fields the electrons are characterized by the extreme distribution function with the population inversion.

Keywords: Ballistic transport; overshoot; III-nitrides

Apendix-6

Wide band-gap light emitters with improved hole injection

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Abstract:

The difficulties in achieving high hole concentrations in group-III nitrides originate from high values of activation energy of acceptors. The average hole concentration can be increased in a p-doped nitride superlattice (SL). However, most of the holes ionized from the acceptors are localized inside the quantum wells (QWs) and cannot participate in vertical transport utilized in traditional light-emitting devices (LEDs). In this report we propose two novel solutions of the problem of hole injection enhancement in wide band-gap LEDs.
Low-intensity emitters: The conventional LEDs can be modified by introducing a two-terminal hole injector that consists of a p-doped SL-base with two contacts. A bias voltage applied between these contacts provides lateral hole acceleration and increases the effective hole temperature. This results in significant enhancement of overbarrier hot-hole concentration. The proposed LED can be thought of as a three terminal device, where the hot-hole SL-injector is placed on the top of heterostructure with an intrinsic i-layer, and an n-doped region. In the report, we discuss parameters of the nitride-based hot-hole injectors and characteristics of the three terminal UV-LEDs.
High-intensity lateral current pumped emitters: To achieve high-density electron-hole plasma (EHP) and interband population inversion in group-III nitrides, we propose a planar p-i-n structure created in selectively-doped SLs: a region doped with acceptors is followed in lateral direction by an i-region and, finally, by an n-region. Thermal activation of the dopants supplies carriers into the QW layers. The QW layers accumulate both types of free carriers and a lateral p-i-n structure is formed.

Presentation: invited oral at E-MRS Fall Meeting 2003, Symposium A, by V A. Kochelap

Submitted: 2003-07-10 12:48
Revised: 2003-07-10 12:50
